

Analysis of slope stability to determine the causes of collapse the primary canal in the North-Raman irrigation-area, Central Lampung

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Abstract. A 25-meter primary-canal in the North-Raman Irrigation-Area (NRIA) collapsed in December 2021. Before the landslide occurred, the rainfall intensity reached 153 mm/hour. Field surveys at the time of the incident revealed that a large enough discharge overflowed from the Raman River, inundating the NRIA. This shows that landslides were most likely triggered by groundwater infiltration due to either high intensity rainfall or flooding. The soil conditions are also unable to support the primary-canal embankment. The present research objective is to carry out slope stability analysis to determine the causes of collapse of the NRIA embankment using the Geo-Slope and Plaxis 8.6 numerical models. Soil parameters are tested and measured in the field and laboratory. The safety factor (SF) at the study site is determined by both models, and then compared with the allowable SF to assess slope stability which should be bigger than 1.5 if no earthquake occurs. However, the Geo-Slope model produces an SF of 0.97. This means that the embankment is very vulnerable to landslides. The laboratory result reinforces this finding where embankment void-ratio is 1.5 (high). A high void ratio can cause water infiltration into the soil, thereby reducing soil stability and bearing capacity.

1 Introduction

Landslides are phenomena occurring on slopes when they are unstable due to the synergistic effect of certain factors such as soil conditions, topography, and vegetation, combined with external factors known as dynamic triggering factors such as rainfall, snow, earthquakes, and human intervention [1, 2].

Most previous studies have identified that in addition to geological, geotechnical, and topographical factors, landslides can be triggered by rainwater that flows as overtopping or piping during the rainy season [3-8]. When rainwater infiltrates the soil, pore water pressure increases [9-13]. Positive pore water pressure causes capillarity, leading to a rise in the groundwater table [10]. High soil saturation weakens the bonds between soil particles, reducing soil shear strength and resulting in instability [14-16]. The rapid increase in upstream water levels leads to high seepage pressure, potentially initiating internal erosion that can develop into piping paths. Continuous particle loss due to piping increases the soil void ratio while decreasing the friction angle, creating a more porous soil structure and dramatically increasing soil erodibility [1].

In December 2021, a 25-meter long primary-canal embankment collapsed in the North-Raman Irrigation-Area, Central Lampung, Pekalongan Regency (Fig. 1). This irrigation primary-canal crosses a river that flows to

the left. Before the landslide occurred, the rainfall intensity reached 153 mm/hour, the river water overflowed and hit the right side of the irrigation canal. [17]. Under these conditions, rainwater infiltration into the soil will most likely increase soil water content and pore pressure around the primary-canal embankment. All of this causes the soil bearing capacity to decrease resulting in landslides. To ascertain the causes of the landslide, it is important to carry out slope analysis at the landslide location by considering the intensity of rainfall.



Fig. 1. The primary canal in the North-Raman irrigation-area collapsed

Slope failure generally occurs on planes characterized by sloping surfaces that are influenced by gravitational

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forces. For example, canal embankment with extreme slopes so that the gravitational force exceeds the plane shear-angle, resulting in landslides [4]. There are two types of landslides, namely translational landslides and rotational landslides [9]. Translational landslides involve the movement of soil and rock along nearly flat or gently undulating slip planes. In contrast, rotational landslides occur along concave slip planes. This last type is common in Indonesia, especially in areas of contact between weathered soil zones and bedrock. Translational landslides usually have shallower slip planes and relatively thin weathering zones [9].

Two methods are commonly employed in slope stability analysis. They are the limit equilibrium method (LEM) and the finite element method (FEM). Both methods predict landslide heights, with findings generally indicating comparable results between FEM and LEM [14]. Geo-Slope or Plaxis 8.6 are software packages used for geotechnical numerical simulation based on LEM [17]. Both models are often useful to determine how sensitive the stability of a structure is to variation in a certain parameter. Previous researchers who used the Geo-Slope model to analyse slope stability stated that the results were satisfactory [14-16].

The present research objective is to carry out slope-stability analysis to determine the causes of collapse in primary-canal embankment in the North-Raman Irrigation-Area, Central Lampung, Pekalongan Regency using the Geo-Slope and Plaxis 8.6 numerical models. This study will provide essential information which is required to improve the design of hydraulic infrastructure affected by landslide-prone embankments.

2 Methods

2.1 Research site

This research was conducted at the location of the primary canal that collapsed (BRU-1B at STA 5,375) in the North-Raman Irrigation-Area, Pekalongan Regency, Ganti Mulyo Village, Central Lampung. Dimension of the irrigation canal is presented in Fig. 2. The location coordinates are 5°2'24.96" S - 105°21'41.4" E. Fig. 3 shows the research site.

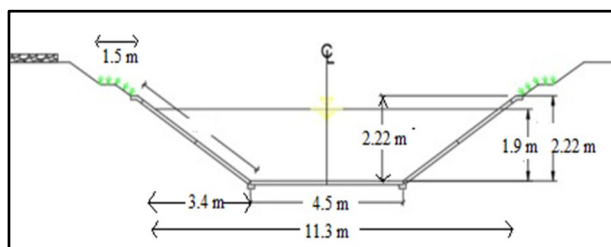


Fig. 2. Dimension of irrigation canal

2.2 Data collection

The data collected for the purposes of this study are rainfall data, geological data and soil properties. Daily

rainfall data at the landslide location was obtained from BMKG Central Lampung. The rainfall station is the closest station to the landslide location. Geological data and soil properties were obtained from field surveys and the Geological Map of Central Lampung (Fig. 4). Fig. 5 depicts soil sampling (drill holes) carried out at BRU-1B at STA 5,375 to a depth of 10 meters. The required soil properties are soil unit weight γ in kN/m^3 , soil specific gravity G_s , effective cohesion c' in kN/m^2 , effective shear angle ϕ , void ratio, soil permeability, compression index C_c , consolidation coefficient C_v , average water content in percentage, and groundwater level.

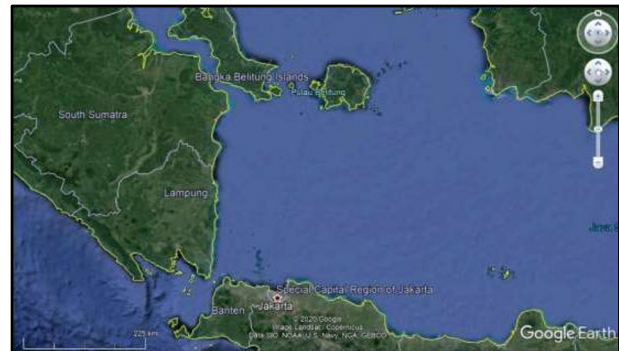


Fig. 3. Research site

2.3 The limit equilibrium method

The LEM is the theoretical basis of the Geo-slope model. This method is used to predict slope stability based on the comparison between supporting forces and driving forces acting on the slope. The results of this comparison are referred to as safety factors (SF). The SF values that represent slope-stability conditions are presented in Table 1. The simplest equilibrium method is the wedge method. The wedge method is one of the most basic approaches to assessing slope stability. This method involves dividing the slope into several vertical slices and analysing the forces acting on each slice. Overall stability is then determined by adding up the forces from all the slices and calculating a safety factor. The derivation of these forces is explained in Fig. 6 and Equation 1.

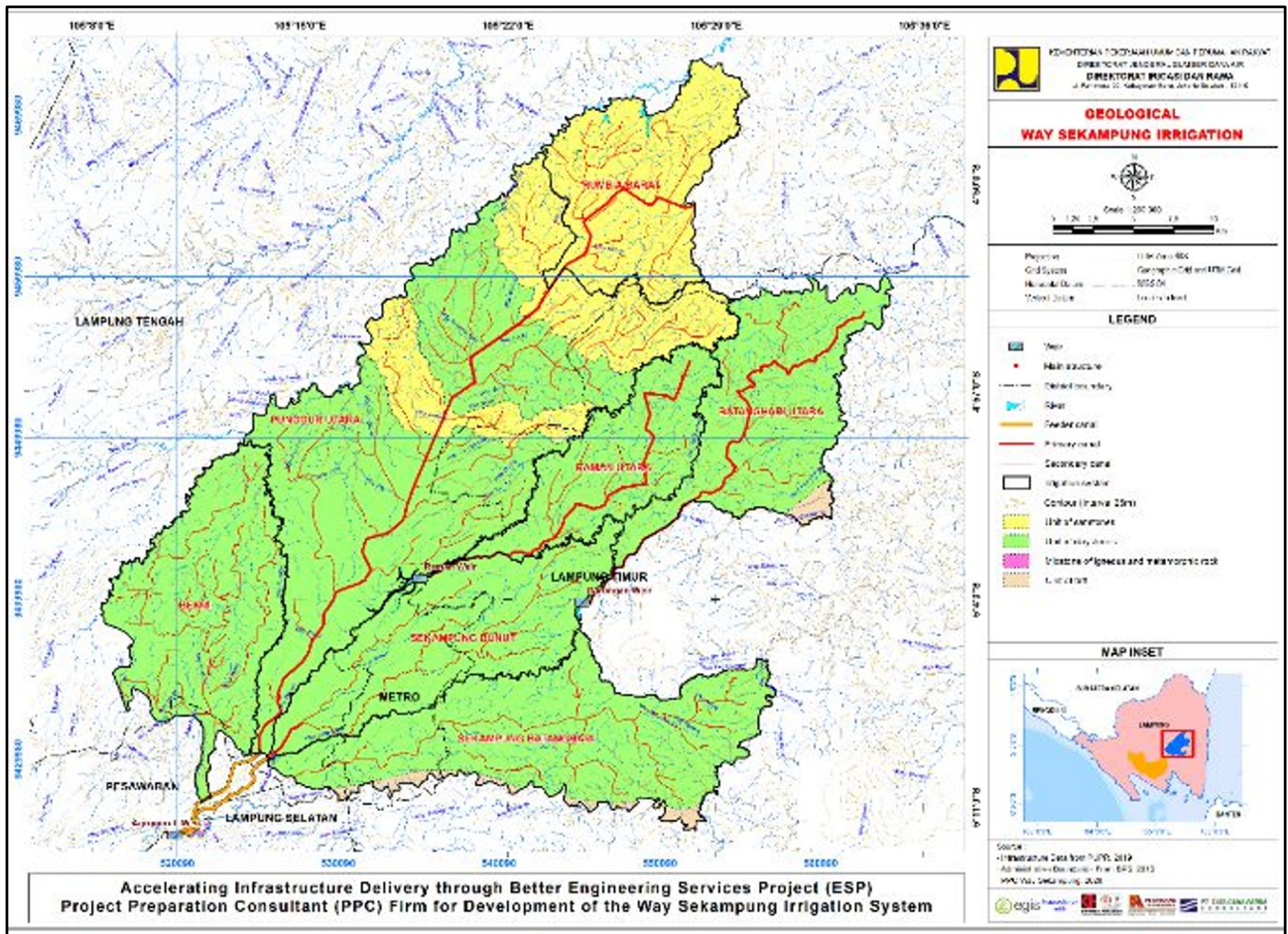


Fig. 4. Geological map in the Central Lampung

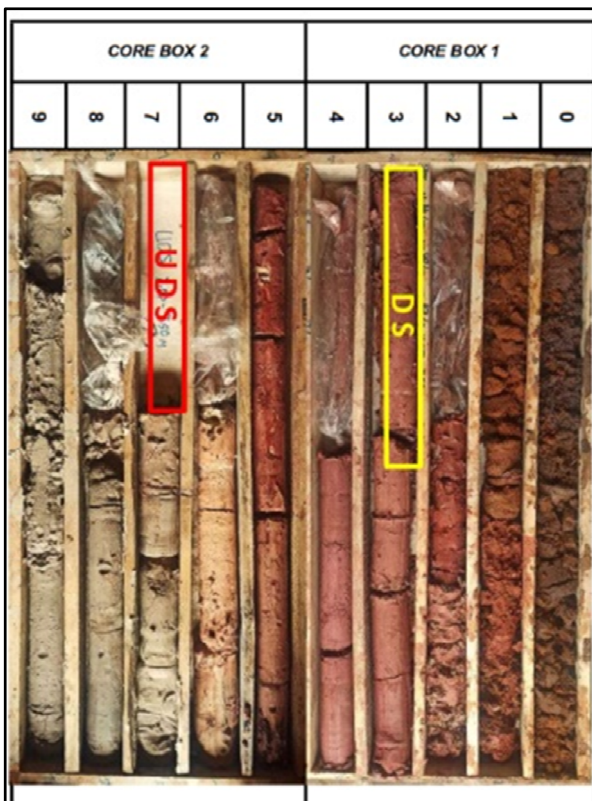


Fig. 5. Borehole sampling at BRU-1B di STA 5,375 up to 10 meters depth

Table 1. Relationship between *SF* values and landslide intensity

No	<i>SF</i> Values	Landslide Intensity
1	< 1.07	Landslides are common/frequent
2	1.07 < <i>SF</i> < 1.5	Landslides occur occasionally
3	> 1.5	Landslides are rare

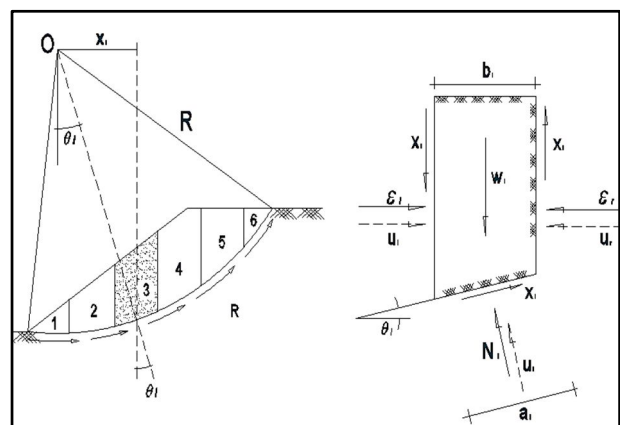


Fig. 6. Dividing the slope into several vertical slices

$$SF = \frac{\sum_{i=1}^{i=n} (c' a_i + N_i \phi') R}{\sum_{i=1}^{i=n} (W_i + \sin \theta_i) R} \quad (1)$$

Where *SF* is safety factor, *R* is radius of the landslide circle (m), *c'* is effective cohesion (kN/m²), ϕ' is effective shear angle (°), *u* is pore water pressure, *W_i* is weight of the slide, $N_i = W_i \cos \theta_i$ is normal force on each slice, *a_i*

is circle curve length (m) and θ_i is slope angle of each slide.

3 Results and discussion

3.1 Landslide type

The primary canal in BRU-1B at STA 5,375 has a base width of 11.3 meters, height of 8 meters, and the width of the top of the embankment is 1.5 meters. The 25-meter length of this canal which consists of a right embankment and a 4.5-meter-wide base, collapsed into the river and rice fields. As a result, the North-Raman Irrigation-Area stopped operating. In an addition, 4000 hectares of rice fields cannot be irrigated by this irrigation canal. Visually, the landslide that occurred was identified as a translational landslide where the sliding surface formed a straight line. Fig. 7 shows the condition of the channel before and after the landslide.



Fig. 7. The primary canal: before landslide (top) and after landslide (bottom).

3.2 Void ratio

The void ratio in soil greatly influences its mechanical properties. The greater the pore number indicates the greater the soil's ability to hold water, thus affecting its stability and carrying capacity. In addition, the void ratio impacts soil permeability, namely the soil's ability to pass water or other fluids. The void ratio can reflect changes in the internal structure of the soil. A high void ratio allows water infiltration into the soil or piping. When piping

occurs, fine particles are continuously lost in the flow, resulting in the volume of soil cavities increasing and the microstructure becoming looser so that the possibility of landslides is greater.

Fig. 8 presents the void ratio at the landslide location during the consolidation test. Based on the graph, the void ratio at the landslide location is 1.5. This value is quite high, indicating that the volume of voids is greater than the volume of soil grains. Therefore, it can be concluded that the high number of pores at the landslide location allows water infiltration into the soil, thereby reducing the stability and bearing capacity of the soil. The high void ratio at the landslide location causes the soil structure to become more porous and increases soil erodibility significantly.

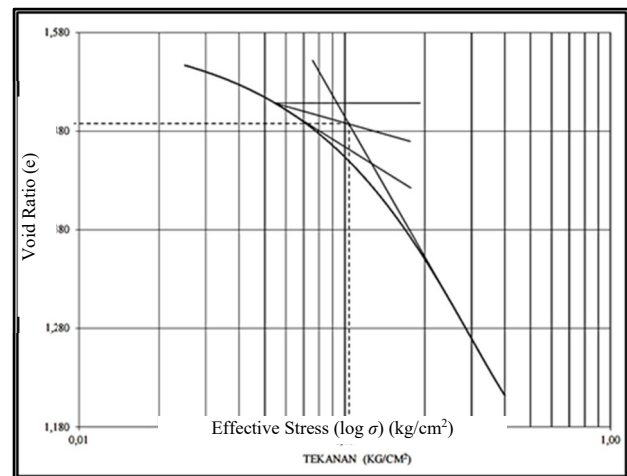


Fig. 8. Void ratio at the landslide location during the consolidation test

Table 2. Soil properties

Soil parameters	Depth of soil		
	2.5 m	7 m	
SPT	14	3	
Type of soils	Silty clay (cm/s)	Silty clay	
Soil permeability	2.6×10^{-6} (cm/s)	8.4×10^{-5} (cm/s)	
γ_t	17.5 kN/m ³	17.5 kN/m ³	
Specific gravity (G_s)	2.699 gr/cm ³	2.335 gr/cm ³	
Groundwater level	7-8 m		
LL	86 %	70.47 %	
PL	50 %	49.62 %	
IP	35 %	20.86 %	
Particle size analyses	Gravels	0 %	11.25 %
	Sand	11.6 %	11.84 %
	Silt	15.7 %	56.34 %
	Clay	73.24 %	20.57 %
Consolidation test	C_c	-	0.411
	C_v	-	8.6×10^{-4} cm ³ /s
Triaxial UU	ϕ' (°)	0	5.954
	c'	0	0.144 kg/cm ²

3.3 Slope-stability analysis using geo-slope model

To analyse the impact of rainfall infiltration on slope stability using Geo-slope model, the following parameters

are required: rainfall intensity in mm/h, slope angle in degrees, soil depth Z , ground water level in meters, soil type, soil permeability k , cohesion to effective stress c' , angle of internal friction to effective stress ϕ' , and total unit weight of soil γ_t . By using these variables, the soil is assumed to be in the most critical and saturated condition due to high rainfall intensity.

The data required for the simulation is presented in Table 2. The data in this table are the results of laboratory tests. Testing was carried out using the undrained consolidated (UC) triaxial test method.

Fig. 9 shows the results of simulating the conditions of the irrigation canal-slope using Geo-slope model. The model results show that the safety factor is 0.97. Based on Table 1 regarding the relationship between SF values and slope conditions, the SF value below 1.07 indicates a high risk of landslides. Therefore, it can be concluded that the condition of the slope at the landslide location is classified as critical, where there is a high probability that frequent landslides will occur. By taking into account the SF and surface slip obtained from the Geo-slope model, these results are considered close to existing conditions.

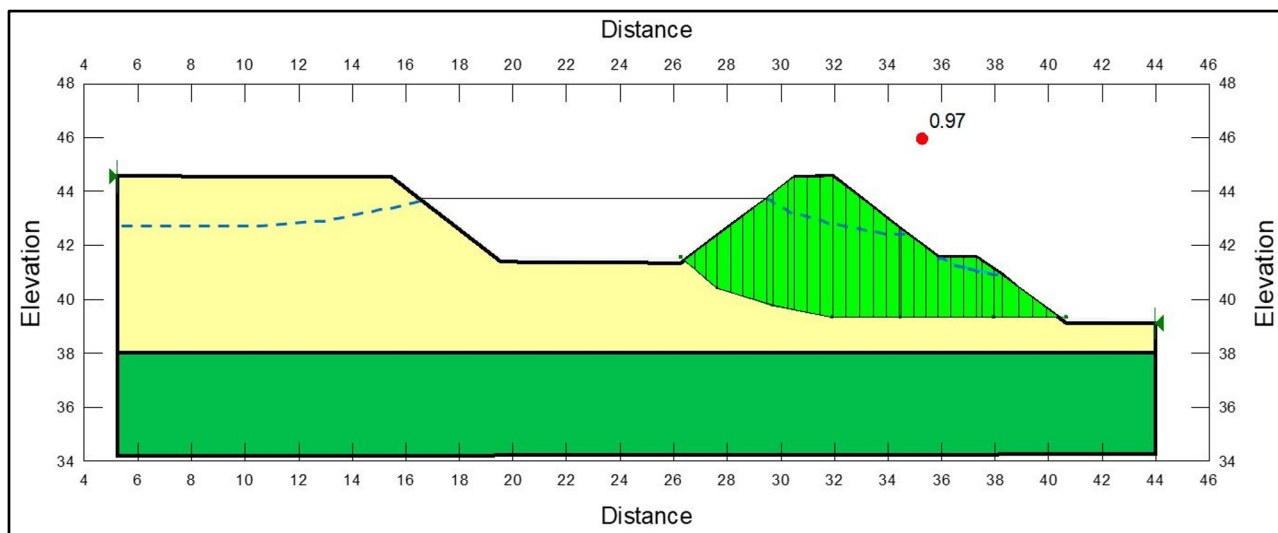


Fig. 9. Simulation results of irrigation canal-embankments using the Geo-slope model

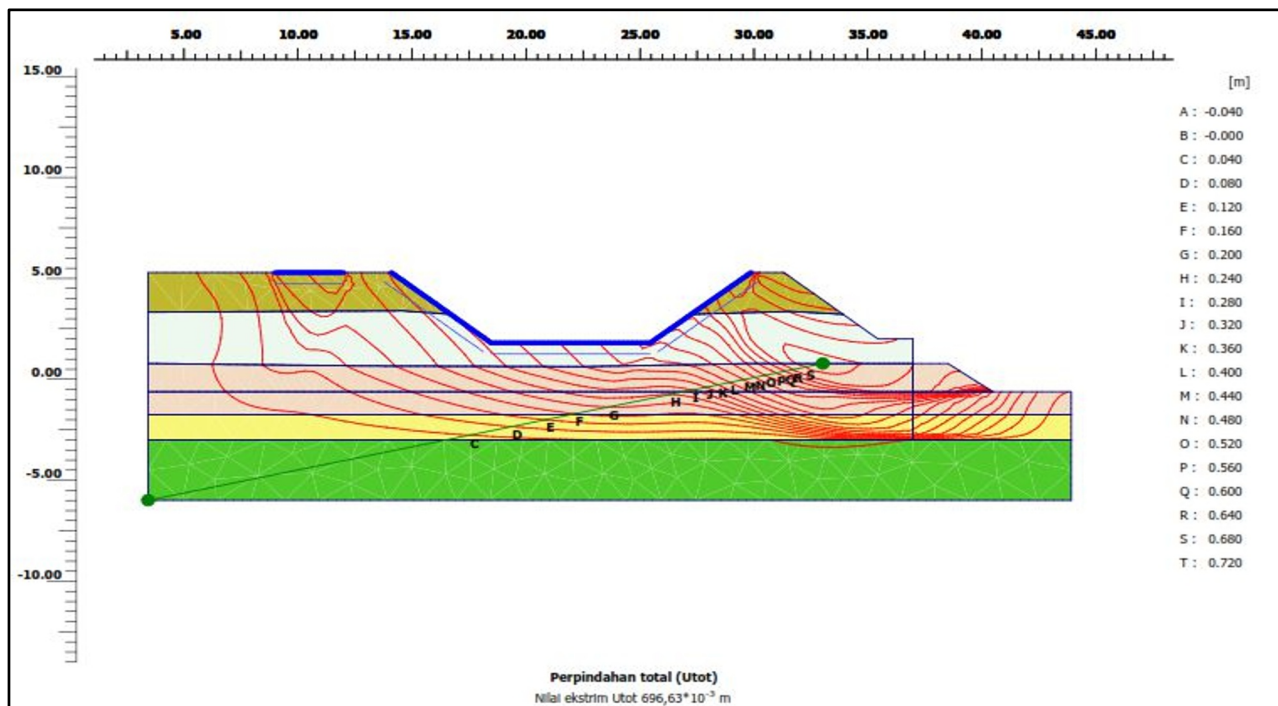


Fig. 10. Simulation results of irrigation canal-embankments using the plaxis 8.6 model

3.4 Slope-stability analysis using plaxis model

Based on simulation results using the Plaxis 8.6 model, the potential horizontal nodal displacement U_x is 0.69

meters (Fig. 10). This is in line with landslide conditions in the field, where the movement of landslide material reaches a distance of less than 1 meter. Positive values indicate movement to the right, while negative values indicate movement to the left. Soil elements that

experience horizontal displacement are influenced by factors such as excess pore water pressure and the weight of the soil itself.

4 Conclusions

The results of the analysis of the slope stability of the primary-canal embankment in the Raman-North Irrigation-Area using two numerical models, namely the Geo-slope and Plaxis 8.6 models, show that the BRU-1B location is very prone to landslides. This can be indicated by a low safety factor (*SF* of 0.97 at the landslide location which is far below the allowable *SF*). This finding is also reinforced by laboratory results where void ratio (*e*) at the landslide location is classified as high, it is around 1.5. A high void ratio can cause water infiltration into the soil, thereby reducing soil stability and bearing capacity.

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